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# Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications

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**Abstract**

Through the support of the US Department of Energy, Clean Energy Systems, Inc. and its development partners have designed, manufactured, and tested and industrial-scale oxy-fuel turbine, suitable for applications in oxy-combustion power cycles that capture greater than 99% of produced carbon dioxide. To save on development cost and schedule, a used industrial gas turbine, an SGT-900 B11/12 engine, was purchase, disassembled and inspected, then retro-fitted to act as an intermediate-pressure, hot gas expander. Also, the engine's air-breathing combustors were converted into oxy-fuel reheaters to boost turbine inlet temperatures and therefore, cycle efficiencies. A dedicated test rig was designed, fabricated, instrumented, and installed at an existing test facility to demonstrate reheater performance prior to install and operations within the oxy-fuel turbine. Component test results prove the feasibility of gas turbine conversion to oxy-fuel turbine, however further testing is recommended to further verify performance at higher power levels, and longer durations.



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*Keywords:* oxy-fuel; O-F; oxy-combustion; oxy-fuel turbine; OFT; enhanced oil recovery; EOR; carbon capture and storage; CCS, carbon capture utilization and storage; CCUS

## 1. Introduction

Future fossil-fueled power generation systems will require emission control technologies such as carbon capture and sequestration (CCS) to comply with government greenhouse gas regulations. The three prime candidate technologies which permit carbon dioxide ($CO_2$) to be captured and safely stored include pre-combustion, post-

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combustion, and oxy-fuel (O-F) combustion. Since the company's inception in 1996, Clean Energy Systems, Inc. (CES) has been designing and demonstrating enabling technologies for oxy-fuel power generation; specifically steam/gas generators, hot gas expanders, and reheat combustors [1, 2, 3].

Recently CES partnered with Florida Turbine Technologies, Inc. (FTT) and Siemens Energy, Inc. (Siemens) to develop and demonstrate turbomachinery systems compatible with the unique characteristics of O-F working fluids. The team has adopted an aggressive, but economically viable development approach to advance turbine technology towards early product realization. Goals include short-term, incremental advances in power plant efficiency and output while minimizing capital costs and cost of electricity.

The second phase of this development work has been greatly enhanced by a cooperative agreement with the United States (US) Department of Energy (DOE). Under this program the team has designed, manufactured, and tested a commercial-scale intermediate-pressure turbine (IPT) to be used in industrial O-F power plants. These plants will use diverse fuels and be capable of capturing 99% of the produced $CO_2$ at competitive cycle efficiencies and cost of electricity. It is postulated that initial plants will burn natural gas (NG) and generate more than 200 MWe with near-zero emissions.

**Nomenclature**

| | | | |
|---|---|---|---|
| ARRA | American Recovery and Reinvestment Act | IPT | intermediate-pressure turbine |
| ASU | air separation unit | KPP | Kimberlina Power Plant |
| BOP | balance of plant | $LCO_2$ | carbon dioxide liquid |
| CCS | carbon capture and sequestration | LOX | liquid oxygen |
| CCUS | carbon capture, utilization and sequestration | LP | low-pressure |
| CEMS | continuous emissions monitoring system | LPT | low-pressure turbine |
| CES | Clean Energy Systems, Inc. | $N_2$ | nitrogen gas |
| $CH_4$ | methane gas | NETL | National Energy Technology Laboratory |
| CO | carbon monoxide | NG | natural gas (US pipeline quality) |
| $CO_2$ | carbon dioxide gas | NOx | nitrogen oxides |
| Cp | specific heat | $O_2$ | oxygen gas |
| CW | cooling water | O-F | oxy-fuel |
| DOE | U.S. Department of Energy | OFT | oxy-fuel turbine |
| EGR | enhanced gas recovery | PF | pattern factor |
| EOR | enhanced oil recovery | RH | reheater or reheat combustor |
| FTT | Florida Turbine Technologies, Inc. | TC | thermocouple |
| GT | gas turbine (engine) | TIT | turbine inlet temperature |
| GG | gas generator (oxy-fuel combustor) | $T_{exh\ max}$ | maximum measured exhaust temperature |
| $H_2$ | hydrogen gas | $T_{exh\ ave}$ | average measured exhaust temperature |
| HP | high-pressure | $T_{in\ ave}$ | average inlet temperature |
| HPT | high-pressure turbine | US | United States of America |
| HX | heat exchanger | Siemens | Siemens Energy, Inc. |
| IP | intermediate-pressure | WF | working fluid |

## 2. The oxy-fuel cycle

A representative O-F power cycle is shown in Figure1. It begins with an air separation unit (ASU) that generates nearly pure oxygen ($O_2$) that is fed to the primary O-F combustor, also known as a gas generator (GG). The GG combusts the gaseous $O_2$ directly with a selected fuel (usually a gaseous hydrocarbon) to produce a hot gas stream comprised predominantly of steam and $CO_2$. Utilizing recycled water and/or $CO_2$, the hot gas is cooled within the GG to the desired temperature of a high-pressure turbine (HPT) before it is reheated and further expanded through an intermediate and low-pressure turbine (IPT and LPT respectively). Since the working fluid (WF) is comprised of primarily steam and $CO_2$ it is easily separated in a condenser to produce high purity $CO_2$, viable for sequestration, enhanced oil recovery (EOR), or enhanced gas recovery (EGR), and excess water.

The HPT and LPT in this cycle can be implemented using existing steam turbine technology as the operating temperatures are, in general, modest. High operating temperatures within the IPT however has been found critical to overall cycle efficiency [4, 5]. Studies have shown that competitive cycle efficiencies and cost of electricity is achieved when operating with an IPT inlet temperature of 1,400 - 2,280ºF (760 - 1,250ºC) [6, 7, 8] which is well above the capabilities of traditional steam turbines. Gas turbine engines (GT) however routinely operate within this range because of sophisticated materials and cooling technology within the turbine. The development team has found that these engines can be adapted to accept the high-steam content working fluid of the O-F cycle with minimal modification.

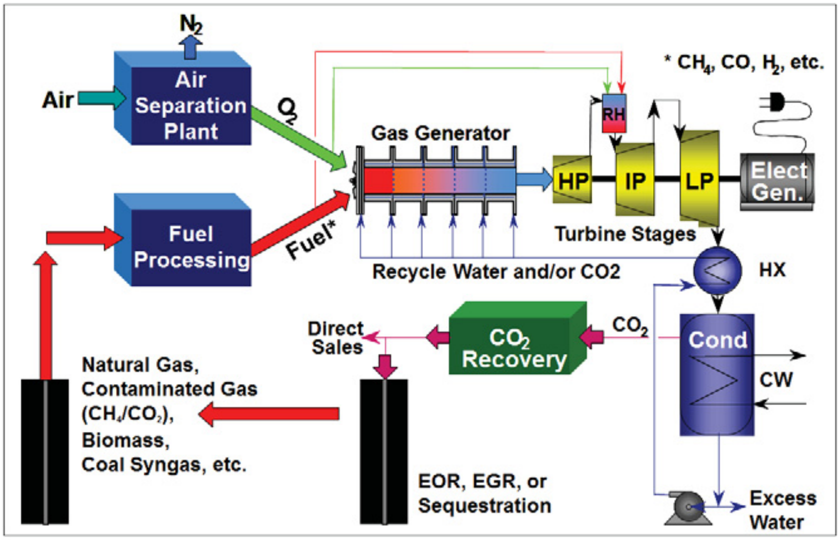


Fig. 1. Schematic of the CES oxy-fuel power cycle

The topic of this paper is the development of an industrial-scale O-F IPT, capable of generating up to 150 MWe. The O-F cycle utilizing this modified gas turbine engine would start with the GG combusting NG to produce hot expansion gas comprised of steam and ~10 mol% $CO_2$. The HPT would operate at between 1,150 to 1,450 psia (80 to 100 bara) with an inlet temperature near 1,050°F (~565 °C), as is typical for conventional steam turbines. The main technical challenge for the HP turbine is the choice of materials for rotating parts that are in direct contact with the steam / $CO_2$ WF which can also contain ~1 mol% $O_2$. In this cycle the HP turbine will produce about 20% of gross plant power output.

The LP turbine operates at typical geothermal steam turbine conditions and therefore poses a less of a technical challenge with inlet temperature typically below 750°F (400°C) and pressure from 30 psia (2 bara) down to sub-atmospheric, dependent upon condenser performance. However optimized performance in combination with the condenser section is also an important consideration because the LP part of the cycle can produce up to 30% of the gross plant power output.

The IP turbine poses the most significant technical challenge because following reheating, the predominantly steam working fluid now includes ~15 mol% of $CO_2$ at a temperature that is preferably well above that of conventional steam turbine operations and more akin to the gas turbine temperature and pressures. Even with a moderate operating pressure of approximately 230 psia (~16 bar) the IPT will produce over 50% of gross plant output. For this reason the merging of the Brayton and Rankine cycles is the essence of the oxy-fuel turbine (OFT) challenge that is being addressed for commercial-scale hardware by the work reported in this paper. To achieve the necessary economies of scale it is also evident that a power generation turbine, rather than an aero derivative, would need to be selected for the present program.

Overall, this cycle produces roughly 290 MW gross using a practical limitation on OFT's turbine inlet temperature (TIT) of 2,050°F (~1,120°C). Assuming typical parasitic loads for balance of plant (BOP) equipment – including the ASU and $CO_2$ compression and cleanup to pipeline specific conditions – the net power export would be 215 MWe. Although overall thermal efficiency remains low for this first demonstration unit, analyses shows that more competitive cycle efficiencies (and cost of electricity) are achieved when TIT approaches 2,280ºF (1,250ºC) and above, as is routinely achieved in conventional gas turbines through use of advanced materials and cooling technology within the turbine.

## 3. Background

CES was founded in 1993 and has its origins from the aerospace industry and US Space Programs. The company has specialized in deploying oxygen-based technology developed in rocketry for innovative, flexible, and economically attractive power generation systems that target efficient, compact heat transfer, and the capture of generated $CO_2$ for sequestration or utilization resulting in zero emissions.

For more than a decade advancement of the CES technology portfolio has also benefited with support from the US DOE's National Energy Technology Laboratory (NETL). Already in 2003 the NETL participated in development and testing of a 20 MWt O-F burner, or GG, that eventually completed more than 1,000 hrs of power to grid production and is now a commercially insured unit. In 2005 CES and NETL entered into cooperative agreement DE-FC26-05NT42645 for "Coal-Based Oxy-Fuel System Evaluation and Combustor Development." Successful demonstration of an HP O-F combustor led to an extension of the agreement to support O-F turbine development.

In September, 2010, a modification to the cooperative agreement was awarded for "Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications" under the American Recovery and Reinvestment Act (ARRA) of 2009. The modification added scope for the design and demonstration of a commercial-scale OFT for use in clean, fossil-fuel burning, O-F power plants that capture 99% of the produced carbon-dioxide. Two key decisions were made in order to expedite the demonstration of an industrial-scale turbine with the limited funding and schedule; 1) a used GT would be purchased and modified for the O-F environment, and 2) an existing facility would be used to support low-power demonstration of the turbine, in a simple O-F power cycle.

CES partnered with FTT and Siemens to complete the expanded scope of work, each leading subtasks within their area of expertise. FTT led the detailed engineering design effort to convert a conventional GT to an industrial-scale OFT, Siemens led the work associated with acquiring and adapting the candidate turbine, while CES managed test site development and upgrades as well as OFT install and commissioning. In 2012 the team presented progress to date in a TurboExpo conference paper detailing the selection and acquisition of a used 50 MWe SGT-900 B11/12 gas turbine Econopac plant, the engineering design to convert it into an O-F IPT (renamed the OFT-900) including modifying the existing combustion system into an eight-can annular O-F reheat combustion system, and the initial work to design and upgrade CES' existing Kimberlina Power Plant (KPP) to support low-power OFT demonstration [9]. It is the purpose of this report to complement the 2012 paper by detailing the final test program, its results, and next steps.

Two primary test demonstration phases were completed under the DOE cooperative agreement. The first demonstrated took place in late 2012 – early 2013, and operated a single reheat combustor can, or reheater (RH), in a dedicated test rig, designed to simulate $1/8^{th}$ of the OFT-900 engine. Exhaustive testing was completed at design conditions with a steam-rich, steam and $CO_2$ WF, using pipeline quality NG as the fuel. Later, the rig was modified to allow for some off-design tests with $CO_2$ enhancement of either the WF or the fuel. These tests prove the flexibility of the O-F power cycle to use contaminated fuels (which generate a high-$CO_2$-content WF) and the possibility of a self-sustaining EGR facility using CES combustion technologies. The second demonstration was of the OFT-900 powered by the primary O-F combustor, without firing the eight-can reheat combustion system. This work completed in March, 2013. By demonstrating each the RH and the OFT separately, overall program and development risks were mitigated. Because program funding was consumed upon the completion of these two demonstration phases, the next step of operating the OFT-900 with reheat combustors was unable to be realized, and has been placed on hold indefinitely.

## 4. Test articles

This section describes the prototype equipment that was designed, manufactured, and evaluated during the program. These include a modified SGT-900 B11/12 gas turbine engine, and a single-can O-F reheat combustor designed to operate within the eight-can-annular combustion system of the OFT-900. Figure 2 shows images of both; each with flow from left to right.

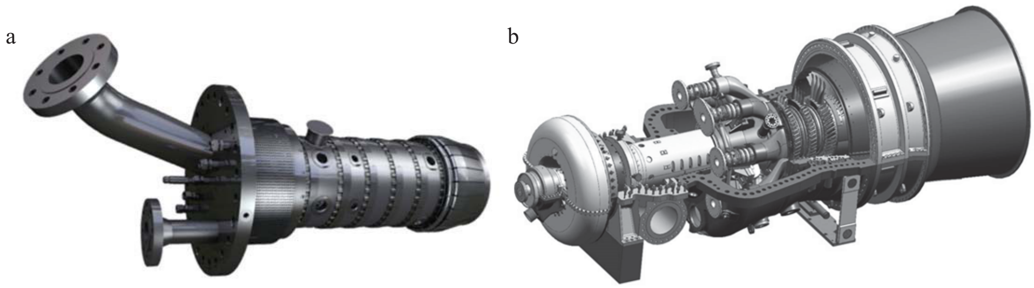


Fig. 2. (a) Single OFT-900 reheat combustor; (b) Solid model of OFT-900, top half removed to show internal details

### *4.1. OFT-900*

An SGT-900 gas turbine engine was selected for modification into an O-F IPT due to its aerodynamic and thermodynamic performance, turbine size, firing temperature and pressure conditions, cooling system functionality, and the flexibility to incorporate necessary configuration changes to ensure mechanical integrity. Additional considerations included the availability of surplus equipment and access to technical data on the engine and auxiliary equipment.

When designing the engine's conversion to accept the O-F drive gas, the general philosophy was to keep the modifications minimal for this first, proof-of-concept unit; especially since initial tests were to be performed in a low-power, simple-cycle, short duration demonstration. That is, only perform the required modifications for OFT demonstration at similar or lower temperature and pressure than the original GT design specifications.

Necessary modifications of the SGT-900 to enable use in the O-F cycle include: 1) the air inlet manifold and axial compression system is removed and replaced by steam intake and duct system to accept the HP WF from an external source and direct it toward a reheat combustor system, 2) the conventional combustors are replaced by O-F steam/$CO_2$ reheaters, 3) a rotor thrust balance system is incorporated to reduce high thrust bearing loads which resulted from the compressor removal, and finally 4) a row of turbine exit guide vanes is installed to deswirl the exhaust flow which resulted from the change in WF – otherwise the turbine section remains unmodified. Further details describing design considerations undertaken by FTT are available in Reference [9].

Of course the central change from GT to OFT was from an air-based WF, to a steam/$CO_2$ WF. The properties of the O-F WF affect the aerodynamic and thermodynamic performance of the turbine. Steam has a significantly higher specific heat (Cp) than air and therefore produces more power at a given mass flow rate. In this case, the WF of the OFT-900 consists of a mixture of 85-90% steam and 10-15% $CO_2$, resulting in a Cp ~60% greater than the combustion products of a traditional NG and air GT. The effects of increased Cp however are partially offset by the reduced ratio of specific heats and molecular weight of the fluid. So, for a given turbine size, pressure ratio, and inlet temperature, turbine power will typically increase by about 20% when using an O-F WF versus an air-based WF. The design team matched the OFT-900's operating pressures and speed to the SGT's but reduced the turbine's operating temperature. The TIT was reduced by 180°F (100°C) from 2,160°F (1,180°C) to 1,980°F (1,080°C) in order to match the temperatures at the backend of the turbine, eliminating the need for material changes.

Fig. 3. OFT-900 and generator installed at CES KPP

Siemens used FTT designs to complete the conversion of a used SGT-900 B11/12 to a first-of-a-kind industrial-scale OFT in 2011-2012. Figure 3 shows the OFT-900 and 60 MW Brush electric generator set at CES KPP in September, 2012. With the compressor removed, the reconfigured OFT-900 is rated for 145 MWe, nearly three times the rating of the SGT-900. This is typical of the load distribution for an axial compressor-turbine configuration. One implication however is that the maximum specification for shaft and dynamic torque behavior can become a limiting design feature. Another consideration is the relationship between mass flow, axial velocity, and rotational speed that defines velocity triangles and blade incidence angles in the turbine. The extent to which this reduces turbine efficiency has not yet been determined experimentally due to the limited OFT testing to date.

*4.2. OFT-900 single reheat combustor*

The purpose of the OFT's reheat combustion system is to heat the warm steam/$CO_2$ WF exhausted from the HPT to the desired inlet temperature of the O-F turbine with minimal pressure losses. The targets set for the OFT-900 RH is to boost WF temperatures from approximately 600°F (316°C) to 2,000°F (1,080°C), with a total system pressure drop of less than 5%. To accomplish this while still maintaining the overall design philosophy, CES elected to utilize the existing SGT-900 combustion cans but replace the front-end air-fuel swirler nozzles with platelet-based O-F injectors. This injector provides precise mixing of near-stoichiometric ratios of NG and $O_2$ to generate stable, efficient combustion. Some of the warm steam/$CO_2$ WF bypasses the injector for use as combustion and metal temperature control. All gases are fully mixed by the time the reheated WF reaches the turbine inlet.

The engine's RH system is made up of eight O-F combustors operating with an inlet pressure of 238 psi (16.4 bar), each rated at approximately 28 MWt. In order to reduce program risks, a single full-scale reheat combustor can (Figure 2a) was fabricated, instrumented, and installed in a dedicated test rig, designed to simulate the OFT's internal flow conditions. Placement of RH instrumentation, thermocouples (TCs) and pressure transmitters, was guided by results of predictive analyses completed during burner design. TCs used were type K, Inconel sheathed, grounded thermocouples attached with small strips of Inconel sheeting, spot welded into place. Total, static, and differential pressures across the RH were installed in the test system and all mechanical interfaces were maintained to best simulate the actual operating conditions of the combustor in the OFT-900.

## 5. Test facility

In order to reduce development cost and schedule, an existing facility was modified to support OFT-900 testing. CES' Kimberlina test facility, located in Bakersfield, California, already featured onsite storage supplies of compressed NG, oxygen, and deionized (DI) water to feed its two onsite O-F combustors. It was determined early on in the program that this facility could be readily upgraded to accommodate low-power testing of the industrial-scale OFT. Figure 4 is a schematic of the KPP test setup for OFT-900 demonstration.

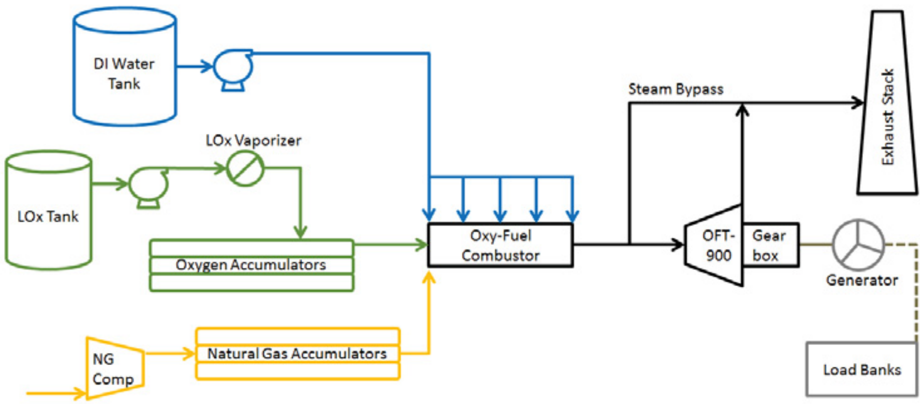


Fig. 4. Schematic of OFT-900 test set-up at CES' Kimberlina test facility

### *5.1. Deionized water system*

The DI water is supplied to KPP by well water that is pumped to site, run through resin ion exchange beds, and stored in a 65,000 gallon supply tank. The quality of the water is less than five parts per million total dissolved solids after treatment. To supply the DI water to equipment during testing, the site's main HP feedwater pump, which delivers 110 GPM at 1800 psi, was used.

### *5.2. Fuel supply system*

The fuel supply system is comprised of pipeline quality NG that is compressed up to 3,200 psi (224 bar) through a series of compressors and stored in accumulators with a total capacity of approximately 240,000 scf. The NG is then fed into the plant's main supply header from which the onsite O-F combustors consume the fuel down to a minimum pressure of 800 psi (55 bar). This corresponds to a usable gas capacity of 7,700 lb, which due to the demands of the industrial-scale OFT, limited test durations to approximately one hour.

### *5.3. Oxygen supply system*

The KPP oxygen system includes an 11,000 gallon liquid oxygen (LOX) tank, a 2.2 gallon per minute LOX pump, a LOX vaporizer, and HP $O_2$ accumulators. The accumulators operate at 3,000 psi providing a total of 467,000 scf of gas. The tank and accumulators equate to a supply of 91,100 lb of oxygen. However, the LOX pump limits the amount of useable gaseous oxygen to approximately 15,800 lb, again limiting testing to short durations only.

### *5.4. Oxy-fuel combustor*

CES' 170 MWt, commercial-scale, O-F combustor (Figure 5) was used to supply a steam/$CO_2$ drive gas to both the OFT-900 and the RH test rig. NG and O2 are combusted at the front-end of the combustor than DI water is injected in stages to cool combustion gases to the desired outlet temperature, nominally 600°F (316°C) for these tests. The produced steam/$CO_2$ WF is then ducted to the site's main steam piping system that connects to an exhaust stack, the OFT-900, and the OFT-900 RH test rig. Remote operating valves allow the GG exhaust to be directed to the stack, the OFT-900 test article, or both, at any time during operation.

a

b

Fig. 5. CES 170 MWt oxy-fuel combustor (a) side view; (b) front view

### *5.5. Power generation and dissipation systems*

The OFT-900 drives a 60MWe Brush electric generator through a Lufkin reducing gearbox. No modifications were necessary to these systems that came with the used SGT-900 Econopac purchase, only minor inspections and refurbishments. The generated power was delivered through an underground duct bank to resistive load banks. The four sets of Avtron load banks purchased and installed at site can dissipate up to 24MWe.

### *5.6. Reheater test rig*

A test rig designed to simulate 1/8$^{th}$ of the OFT-900's reheat combustion system, including a simulated transition piece – used to duct exhaust gases to the O-F turbine's inlet guide vanes – was fabricated, instrumented, and installed at CES KPP. The rig was sized to test a single, full-scale OFT-900 RH at full power for short durations (less than one hour). Special care was taken to ensure all flow paths would replicate the actual conditions inside the OFT-900 engine. Even small leakage rates of steam/$CO_2$ at the combustor's interfaces were incorporated into the design.

Shown in Figure 6, the single-can RH test rig is comprised of four sections: a forward combustor section, an aft combustor section, an instrumentation section, and an attemperator section. The combustor itself is housed in the upstream, or forward, combustor section. This is where the fuel, oxygen, and WF are combined and combusted inside the test article (combustor). The products of combustion are then ducted downstream to the instrumentation section where temperature and pressure profiles are continuously monitored. In the combustor sections, burner mounting points replicate actual OFT engine hardware. Due to the high operating temperatures in these sections, a reverse flow water circuit is used to cool the walls and keep metal temperatures well within safe operating limits. The last section, the attemperator section, injects water into the hot gas path to cool and prepare combustion products for exhaust to atmosphere.

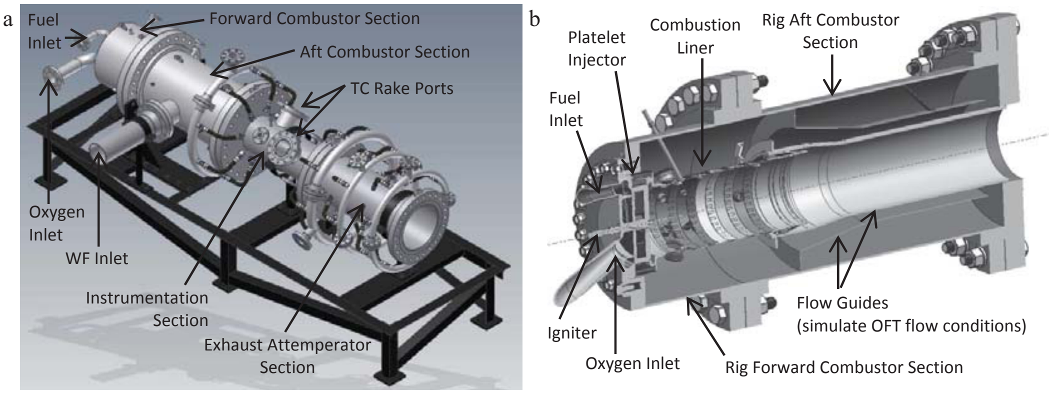


Fig. 6. Solid models of the OFT-900 single-can RH test rig (a) complete test stand; (b) mid-section cutaway of combustor sections

The test rig and all supply systems are heavily instrumented to capture comprehensive performance data during testing. For example, a series of flow measurements, meters, and control valves are used to feed fuel and oxygen to the front of the rig/combustor. The WF is modulated into the side of the rig using a pressure control valve and a steam bypass loop (Figure 7). These flow rates can be ramped to support a single burner operating at 100% power for short durations. The test rig is also equipped with instrumentation to monitor rig and combustor health during operation.

Two key parameters to diagnose RH performance is combustor exhaust temperature and emissions profile. To capture temperature profile data, two air cooled TC rakes, each with eight K-type TCs, are installed in the instrumentation section. The forward rake is rotated 45° clockwise from the rig's top dead center, while the aft rake is rotated 45° counterclockwise off top dead center. Downstream of the rig's attemperator section, a slip stream of exhaust gas is ducted to a continuous emissions monitoring system (CEMS) that captures carbon monoxide (CO), nitrogen oxides (NOx), and $O_2$ emissions (dry basis). These data can then be compared to the CEMS data that are sampled downstream of the primary O-F combustor (upstream of the RH) to deduce any changes in WF composition. Also, bag samples of the dry exhaust gases can be taken from either location during testing for outside laboratory analyses of $O_2$, CO, NOx, hydrogen ($H_2$), and unburned hydrocarbons.

### *5.7. Carbon dioxide supply system*

After the first series of tests of the OFT-900 single-can RH were complete, the rig was upgraded to accept additional $CO_2$ into either the WF or the fuel feed circuits. Liquid $CO_2$ ($LCO_2$) was supplied from a mobile cryogenic storage tank delivered to the site by the local supplier. The tank stored approximately 30 tons (27 tonne) of $LCO_2$ that was maintained at roughly 300 psi (20 bar) by a pressure building coil. When testing, the $LCO_2$ was fed to a series of ambient air vaporizers at flow rates up to 8 lbm/s (3.6 kg/s). This is depicted in the OFT-900 RH test schematic of Figure 7. Due to the limited supply storage and flow rate, RH tests could only be conducted with $CO_2$ flowing to either the WF or fuel circuits, not both.

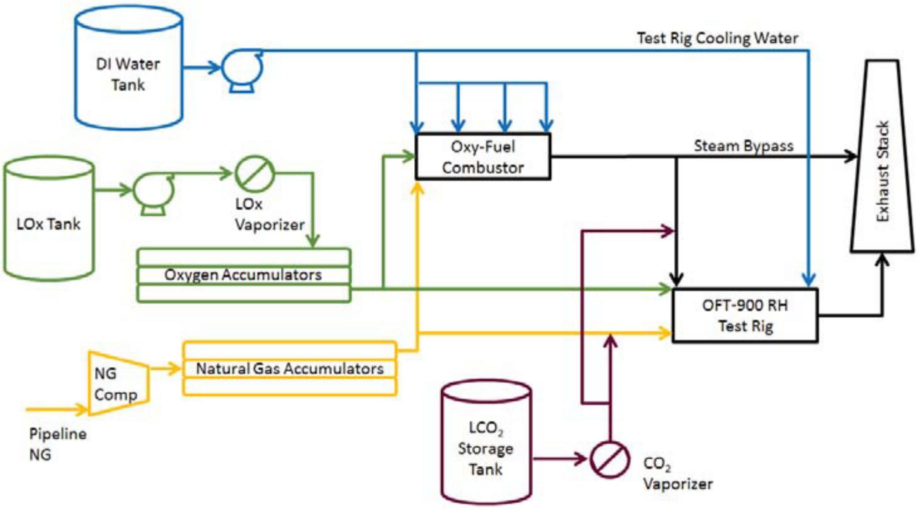


Fig. 7. Schematic of OFT-900 single-can RH test set-up at CES' Kimberlina test facility

## 6. Test results

### *6.1. Results of single-can reheater tests on steam-rich/ $CO_2$ working fluid*

The first test campaign of the OFT-900 reheat combustor demonstrated successful operation on steam-rich/ $CO_2$ WF at heat rates up to 94% of the design value. The injector itself exhibited no damage and performed as designed. The pressure drop across the combustor was between 2.5-3% of the inlet pressure which is better than the design goal of less than 5%. The fuel circuit had a pressure drop between 4.8% and 7.3% of the inlet pressure while the $O_2$ circuit had a pressure drop between 5.3% and 9.9%. The maximum fuel ramp rate achieved was 38%/minute; which was limited by control valves, not the RH hardware.

Pattern factor (PF) is an important parameter used to gage combustor performance by quantifying temperature variations over a cross-section of the combustor exhaust stream. PF is defined as the difference in the maximum measured exhaust temperature ($T_{exh\_max}$) and the average measured exhaust temperature ($T_{exh\_ave}$) over the difference of the average measure exhaust temperature and the average inlet temperature ($T_{in\_ave}$), as shown in Equation 1.

$$PF = \frac{T_{exh\_\max} - T_{exh\_ave}}{T_{exh\_ave} - T_{in\_ave}} \qquad (1)$$

Typical combustors have PFs below 0.15 whereas the design goal for the PF of the CES combustor was 0.10. The measured PFs were between 0.033 and 0.088, far exceeding the design target.

During the test campaign, a large number of operating conditions were run to explore the RHs ignition and operating envelopes. It was found that the RH is capable of ignitions with steam to fuel mass ratios of 70:1 and operation with steam to fuel mass ratios of 80:1. The maximum steam to fuel ratio was not identified. Throughout testing, there were no signs of combustion instability.

The combustor liner suffered some damage when the fuel demand reached 60%-70%. The combustion liner will require some redesign to avoid damage but the redesign does not pose a significant development risk because the sensitive zones were accurately predicted by computational analyses and solutions have been identified. A combustion liner re-design is already underway and will be implemented in the next round of testing where longer test durations at high power levels (up to 105%) are planned. However, due to funding limitations, these tests are on hold indefinitely.

### *6.2. Results of single-can reheater tests on $CO_2$-rich/steam working fluid*

A number of OFT-900 RH tests were performed during the period from Dec. 2013 through Mar. 2014 using the normal $O_2$ and NG supplies and a WF of steam/ $CO_2$ or pure $CO_2$. The steam source for the early tests was the primary O-F combustor, or GG, and the supplemental $CO_2$ came from the commercial $CO_2$ supply system described above. These tests clearly demonstrated that: (1) the OFT-900 RH operating on steam-rich WF, $O_2$, and NG will continue to operate satisfactorily as additional $CO_2$ is introduced into the working fluid, and (2) the RH will successfully start on a steam/$CO_2$ WF significantly enriched in $CO_2$ compared with the normal steam-rich GG exhaust composition.

A series RH light-offs and very short-duration runs was performed using vaporized $CO_2$ from the commercial supply as the sole source of working fluid to the reheater. The average ignition delay based on pressure response times at the fuel inlet was 0.33 sec. These tests demonstrated that the OFT-900 RH reliably and repeatedly starts in a pure $CO_2$ working fluid over a range of startup conditions.

Other RH tests were performed using $CO_2$ from the commercial $CO_2$ supply system to enrich the WF supply to the RH. The operating times and WF inlet pressures ranged from 11 to 65 minutes and 138-153 psi (9.5-10.5 bar), respectively. The $CO_2$ concentration of the steam/ $CO_2$ WF entering the RH ranged from ~41 to 44% vol and the RH firing rate varied from 4.3 to 5.4 MWt (LHV). Total mass flow rates through the RH ranged from 12.9 to13.8 lb/s or ~48000 lb/hr. CO emissions in the RH exhaust were ~0.5-0.7 lb/MMBtu.

From this series of RH tests it was concluded that the current OFT-900 RH has the capability to start and operate reliably with WFs far richer in $CO_2$ that it was designed to accommodate. As examples, the RH reliably started on WFs containing up to 100% $CO_2$ and operated in a sustained fashion on WFs containing up to ~44 % vol $CO_2$, the limit of the test facility, whereas the design basis was ~6% vol. $CO_2$ and 94% vol. steam. The exhaust from theOFT-900 RH was more uniform in temperature than is commonly observed in conventional combustors for GTs.

### *6.3. Results of single-can reheater tests on steam-rich/ $CO_2$ working fluid using $CO_2$-contaminated natural gas*

A series of tests was performed to determine the approximate limit of $CO_2$ in a NG fuel that will sustain combustion while heating a steam-rich steam/ $CO_2$ WF comprised of 94% steam and 6% $CO_2$ by volume, and to determine the approximate limit of $CO_2$ in the fuel that will ignite with O2 in the presence of steam-rich steam/ $CO_2$. Three successful RH flame-out tests defined the upper limiting $CO_2$ concentration in NG to be ~80.0, 79.0, and 78.9 % vol. for the OFT-900 reheat combustor test system. Eleven ignition limits tests defined the ignitable upper limit on the concentration of $CO_2$ in NG with $O_2$ and in the presence of flowing steam/ $CO_2$ WF to be between 79-81% vol.

### *6.4. Results of industrial-scale oxy-fuel turbine tests*

The first round of OFT-900 tests encompassed 20 "hot" tests of the OFT-900 turbine/generator system. These tests did not incorporate the eight reheaters that would normally be integrated in the complete system. The drive gases for the turbine were provided directly by the 170 MWt GG system across 16 runs of the GG. The tests were performed during the period from January to March, 2013. The GG operated on $O_2$, NG and DI water for a total of 3.65 hours at power levels up to 63% of rated power (107 MWt) and mass flow rates up to ~102 lb/sec over the course of the tests. The OFT-900 turbine/generator system operated for a total of 1.84 hours at turbine speeds up to 5,550 rpm, inlet pressures up to 44.6 psig, and inlet steam/ $CO_2$ temperatures up to 522 °F during the series of tests.

The first two OFT tests demonstrated the rapid response of the turbine to the admission of steam/ $CO_2$ drive gases from the GG. The maximum acceleration was ~49 rpm/sec and decreased to 20 to 30 rpm/sec within a few seconds. OFT Runs 3-5 demonstrated automatic turbine speed control at several speeds in the range of 2,000-2,800 rpm by modulation of the by-pass valve to the stack. The maximum turbine acceleration in these tests was ~35 rpm/sec.

Subsequent tests refined the turbine speed control logic and demonstrated automatic turbine speed control by modulation of the drive gas flow rate to the turbine and/or the electrical load on the turbine/generator. Drive gas flow rates up to ~102 lb/sec and electrical loads up to ~1.9 MWe were used in these tests. Modulation of electrical load was found to be a much more responsive and accurate method for controlling turbine speed than modulation of the drive gases to the turbine. Maximum turbine acceleration values ranged from 26-45 rpm/sec and the average maximum acceleration was ~36 rpm/sec. The shortest turbine spin-up time to near-full speed (~5,500 rpm) achieved in these tests was approximately five minutes but shorter times are possible with more rapid ramping of the drive gas supply rate. Several tests demonstrated that the OFT-900 control system will automatically and safely shut down the system whenever a programmed "kill" limit is exceeded.

Turbine vibration issues were observed in the early tests, particularly at the front turbine bearing and near the critical turbine speed (~2,000 rpm). The issues were resolved by re-balancing the turbine rotor and rapidly passing through the critical turbine speed region.

From this first phase of testing, it is concluded that the OFT-900 system functions on O-F steam/ $CO_2$ combustion products at the modest temperatures and flow rates available at the test site in accordance with predictions and expectations. Further testing with the O-F RHs installed and operation at higher drive gas temperatures, pressures, and durations are both desirable and necessary to fully define the capabilities and acceptable operating boundaries of the OFT-900 system.

## 4. Conclusions

Several tests were conducted to prove the feasibility of converting an existing industrial air-breathing GT engine for use as an O-F IPT in commercial-scale O-F power cycles. After detailed design, manufacture, install, and commissioning, component tests were conducted on a modified SGT-900 B11/12 engine and a single, full-scale O-F reheat combustor. These test proved the platelet-based RH design to be very robust, igniting and operating with wide ranges of $CO_2$ in the fuel and WF streams and at very high WF to fuel ratios. The converted SGT-900, named the OFT-900, was demonstrated using a CES GG to provide a warm steam/$CO_2$ WF at low pressure and flow rates to the turbine. The OFT-900 produced power using a standard gearbox and electric generator and proved to be controllable by either modulating the inlet WF stream or generator excitation.

Although these results are encouraging additional testing is recommended to further verify performance of the OFT-900 system. Both the single-can RH and O-F turbine component demonstrations should be conducted again at higher power levels and for longer durations. It is recommended that the combustion liner from the SGT-900 engine not be reused on the platelet-based O-F reheater; instead it should be replaced with a new design, specifically to suit the heat/temperature profile of the O-F RH. The OFT should be operated at higher loads to prove rotor vibration issues have been resolved. Then, the eight O-F reheat combustors should be installed on the engine to verify the performance with increased TIT. This may involve further upgrading the Kimberlina test facility to support the increased demands on NG, $O_2$, and DI water supplies, as well as electrical needs (parasitic and dissipation). At this time, these recommended next tests have been placed on hold indefinitely.

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